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Distribution and classification of pockmarks on the seabed around western Scotland

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ABSTRACT

Pockmarks are seabed depressions that represent primary evidence of rapid biogenic/thermogenic gas build up and fluid release from seabed sediments to the water column. We use a Geographical Information System (GIS) to analyse multibeam echo-sounder bathymetric data and use a range of semi-automated tools to map seabed pockmarks in fjords and adjacent coastal waters around western Scotland. We map 1019 individual pockmarks in 12 different hydrographic areas covering ca. 2019 km². We use morphological metrics and statistical procedures to classify and analyse the variety of pockmark forms. A k-means clustering algorithm identifies three classes of pockmark morphology: deep, elongate and regular. The recognition of separate pockmark classes could aid understanding of their age, activity and origin. This work presents the first detailed mapping of pockmark fields in Scottish west coast waters and highlights the use of pockmarks as an indicator of the quantity, mobility and fate of stored carbon.

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KEYWORDS

Carbon; gas release; classification; GIS; k-means; morphology


1. Introduction

Fjords, firths and coastal seabed sediments are important stores of carbon (Smeaton et al., 2016; Smith, Bianchi, Allison, Savage, & Galy, 2015). Despite fjordic environments being recognised over three decades ago as major carbon stores and globally important natural sequestration sites (Syvitski, Burrell, & Skei, 1987), quantifying the carbon in fjordic and other marine sedimentary systems has remained a largely neglected topic. Two recent studies have provided the first quantitative estimates of total carbon storage buried within Scotland's fjordic sediments (Burrows et al., 2014; Smeaton et al., 2017); however, the results differ strongly. Smeaton et al. (2017) demonstrate that the earlier estimates of organic carbon within Scotland's 111 fjords or 'sea lochs' significantly underestimated the actual total, probably by around three orders of magnitude (0.34 Mt cf 640.7 Mt of C). It is becoming increasingly apparent that the fjordic environments of western Scotland represent a more substantial carbon store (per square metre) than terrestrial equivalents (Smeaton et al., 2016).

Pockmarks are classically described as conical shaped seabed depressions, but can vary greatly in shape and size. They are typically formed by the focused migration and venting of carbon-rich fluids and gases, commonly methane, from the sub-seabed sediment into the water column (Judd & Hovland,

2007). It is widely held that the presence of pockmarks at the seabed reflects the presence or former presence of gas-rich sub-surface sediments (King & Maclean, 1970). Determining the age and activity status of pockmarks can be challenging, however there is a growing agreement that their distribution, density and morphology could be useful indicators of the gas-storage potential of the sediments beneath (Hovland, Heggland, De Vries, & Tjelta, 2010; Krämer et al., 2017). Furthermore the presence of gas release features are a significant geo-hazard to offshore developments (Best et al., 2006). In some cases the presence of submarine structures made by leaking gases can be designated as a Special Area of Conservation (SAC), such as the European designated Scanner pockmark SAC in the North Sea (Gafeira & Long 2015b; JNCC, 2018). Pockmarks have been discovered in many locations on ocean floors worldwide and at a range of depths from >1000 m in the abyssal ocean (Panieri et al., 2017; Pilcher & Argent, 2007) to much shallower settings on the continental shelf (<100 m), providing evidence of their wide bathymetric range. In European waters, gas/fluid-escape related pockmarks have been identified from high-resolution bathymetry and geophysical data in all the shelf seas: in the Mediterranean (Marinaro et al., 2006), Black Sea (Çifi, Dondurur, & Ergün, 2003; Papatheodorou, Hasiotis, & Ferentinos, 1993), Baltic (Whiticar & Werner, 1981), Barents Sea

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(Hovland & Judd, 1988; Solheim & Elverhøi, 1993) and North Sea Basins (Gafeira & Long, 2015a; Judd & Hovland, 2007; Krämer et al., 2017). So far, no inventory or detailed studies have been conducted of pockmarks in Scottish fjords or the adjacent shelf seas west of the UK.

Over the past fifteen years, the inshore (territorial) waters of western Scotland (<12 nautical miles from shore) have been surveyed using a range of different hydro-acoustic multibeam (swath) echo-sounder (MBES) systems, chiefly as part of the Civil Hydrography Programme (CHP) of the UK Hydrographic Office (UKHO), under the auspices of the UK Maritime and Coastguard Agency (MCA). The resulting high-resolution bathymetric datasets provide substantial coverage of the seafloor around Western Scotland with a horizontal (grid) resolution of 1–10 m and a vertical

resolution of generally <0.5 m (Figure 1). A range of seabed gas-release and instability features have been identified from MBES imagery in the fjords and coastal waters of West Scotland, often coupled with other sub-seabed acoustic data (Arosio & Howe, 2018; Hillman, Gorman, & Pecher, 2015; Stoker et al., 2006; Stoker & Bradwell, 2009). The pockmarks previously mapped, from the fjords of Western Scotland, are a testament to the large volume of organic material deposited within these nearshore semi-enclosed basins before, during and immediately after ice-sheet deglaciation (Smeaton et al., 2016, 2017; Stoker et al., 2006).

This paper maps the distribution of seabed pockmarks from MBES data in a range of offshore settings around Western Scotland, all of which contain substantial Quaternary sediment sequences. We then

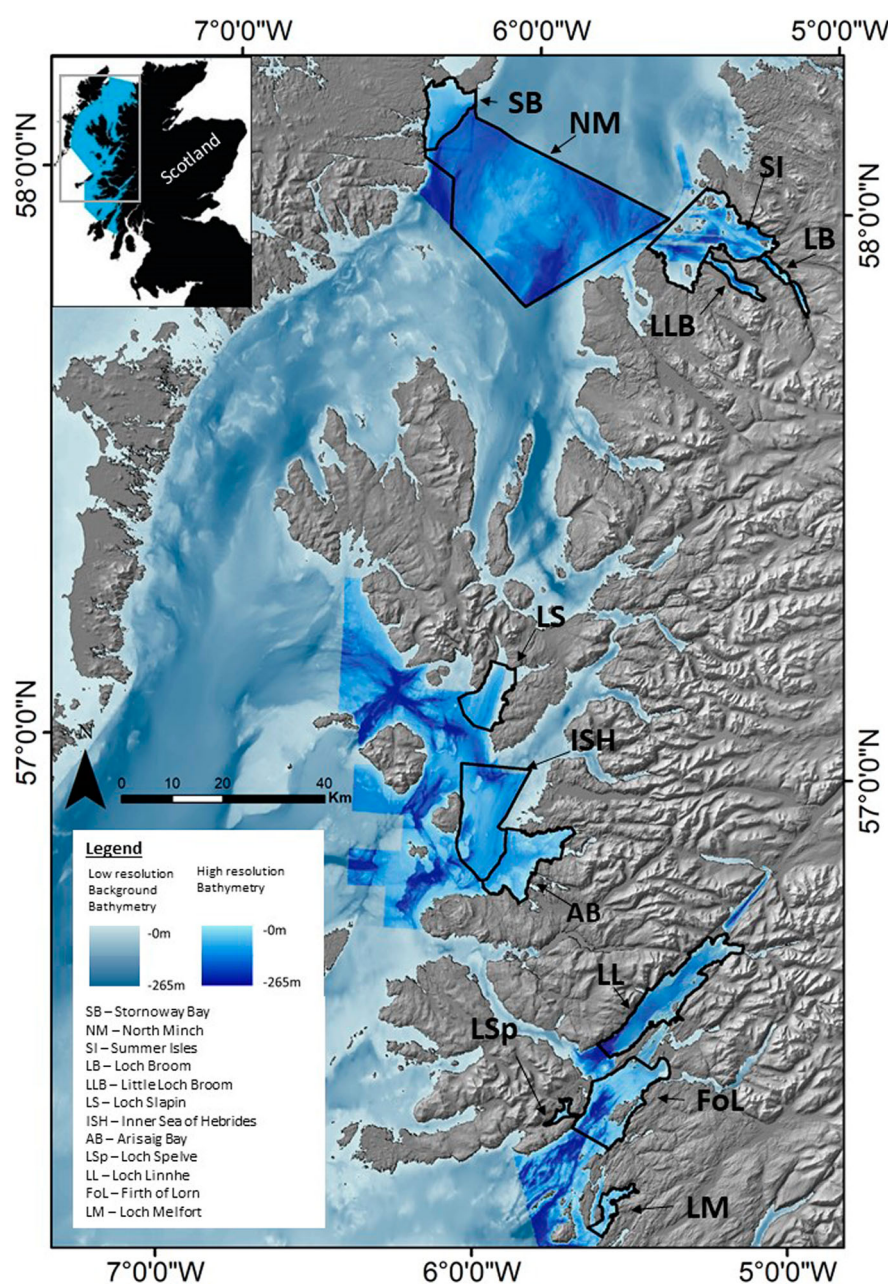


Figure 1. Study sites across western Scotland. Blue region within inset map indicates region designated as a Special Area of Conservation (SAC).

classify these pockmarks based on robust morphological criteria to assess their geographical and bathymetric variability. This work builds a quality-controlled geospatial database of pockmark forms, in a Geographic Information System (GIS), and importantly extends the work of others who have focused on certain Scottish fjords (Howe et al., 2010; Stoker & Bradwell, 2009). The paper is accompanied by a map showing the location, water depth and morphometric summary of all pockmarks so far identified ($n > 1000$) within ca. 2020 km² of coastal waters. This work forms part of a wider study to investigate whether high-resolution hydro-acoustic bathymetry data can be used to reveal the location, extent and fate of carbon stored in seabed sediments around western Scotland.

2. Study sites

We deliberately choose datasets from within different hydrographic and bathymetric settings around Western Scotland. Rather than restricting the study to fjords we extend the geographical scope of this research by including seabed areas further offshore but still within UK internal waters or territorial limits (defined in the *Scottish Adjacent Waters Boundaries Order, 1999*). All these areas experienced a similar style and intensity of glaciation during the last (Weichselian) glacial cycle and share a broadly similar Quaternary stratigraphy (Bradwell, Stoker, & Larter, 2007; Dove, Arosio, Finlayson, Bradwell, & Howe, 2015; Fyfe, Long, & Evans, 1993; Howe, Dove, Bradwell, & Gafeira, 2012). To explore the distribution of pockmarks in western Scottish waters we analysed datasets in the following three, loosely defined, geographical settings:

- (i) **Fjords** – using the definition presented in Howe et al. (2010): glacially over-deepened marine basins that have restricted water circulation due to sills separating the deep waters from the open coastal settings beyond the mouth of the fjord. In this study these fjordic settings include: Loch Broom, Little Loch Broom, Loch Linnhe, Loch Spelve and Loch Melfort. These sea lochs are also classified as fjords by Smeaton et al. (2017).
- (ii) **Fjord approaches and glaciated bays** – these regions lie just outside the mouth of the fjord but typically lie between larger projecting headlands or islands not far offshore (<10 km). These regions are generally wider and more open to marine influences than fjords; but, like fjords, have also been heavily glaciated and contain isolated sediment-filled basins. The hydrographic (tidal and current) regimes are typically stronger in fjord approaches than within semi-enclosed, more protected, fjordic environments. Study areas in this category include: Stornoway

Bay, the Summer Isles, Loch Slapin Approaches, Arisaig Bay and the Firth of Lorn.

- (iii) **Extra-fjordic waters** – these regions are geographically further away from the classical fjords and their approaches, typically being 5–20 km beyond the fjord mouth but, in western Scotland, located within a wider seaway or strait (i.e. The Minch or Sea of the Hebrides). These ‘extra-fjordic’ regions are well exposed to marine influence, but still somewhat protected from the open North Atlantic Ocean by islands to the west (The Outer Hebrides/Western Isles). These regions are the least hydrographically restricted of the three areas, and can be exposed to stronger currents and larger waves. However, like fjords and fjord approaches, these more-distal coastal waters still retain a strong seabed imprint of glaciation and contain a diverse range of sediment-filled basins (Arosio & Howe, 2018; Bradwell & Stoker, 2015; Dove et al., 2015). Study areas within this category include: the North Minch, and the Inner Sea of Hebrides (East of Rum).

3. Data and methods

We use 12 MBES datasets from inshore surveys of Western Scotland collected between 2005 and 2015 by the UKHO. The surveys were conducted to the International Hydrographic Organisation order 1a specification (*IHO Standards for Hydrographic Surveys 2008*) using a variety of research vessels and echosounder models. Multibeam data were processed using CARIS HIPS and SIPS software and gridded at a variety of resolutions from 2 to 12 m. Further details on the data collection process are available from the ADMIRALTY Marine Data Portal (<https://data.admiralty.co.uk/portal/apps/sites/#/marine-data-portal>).

The MBES datasets were imported, viewed and analysed in ArcGIS 10.4 using the BGS Seabed Mapping Toolbox developed by the British Geological Survey (BGS) seabed mapping toolbox (Gafeira, Long, & Diaz-Doce, 2012). The toolbox was set to specifically detect and map confined depressions within each study site (Figure 2) using a bespoke methodology. This workflow involved three main stages: (i) raster preparation, (ii) feature delineation and (iii) statistical classification (Figure 3).

The first stage, raster preparation, was necessary as it is difficult to isolate features based on the bathymetry alone. This is especially true in regions that contained larger sediment-filled basins containing features of interest or in regions with bathymetric artefacts resulting from data collection. The ArcGIS ‘Filter’ tool was used to smooth the bathymetry and remove the effects of artefacts. The next step was to

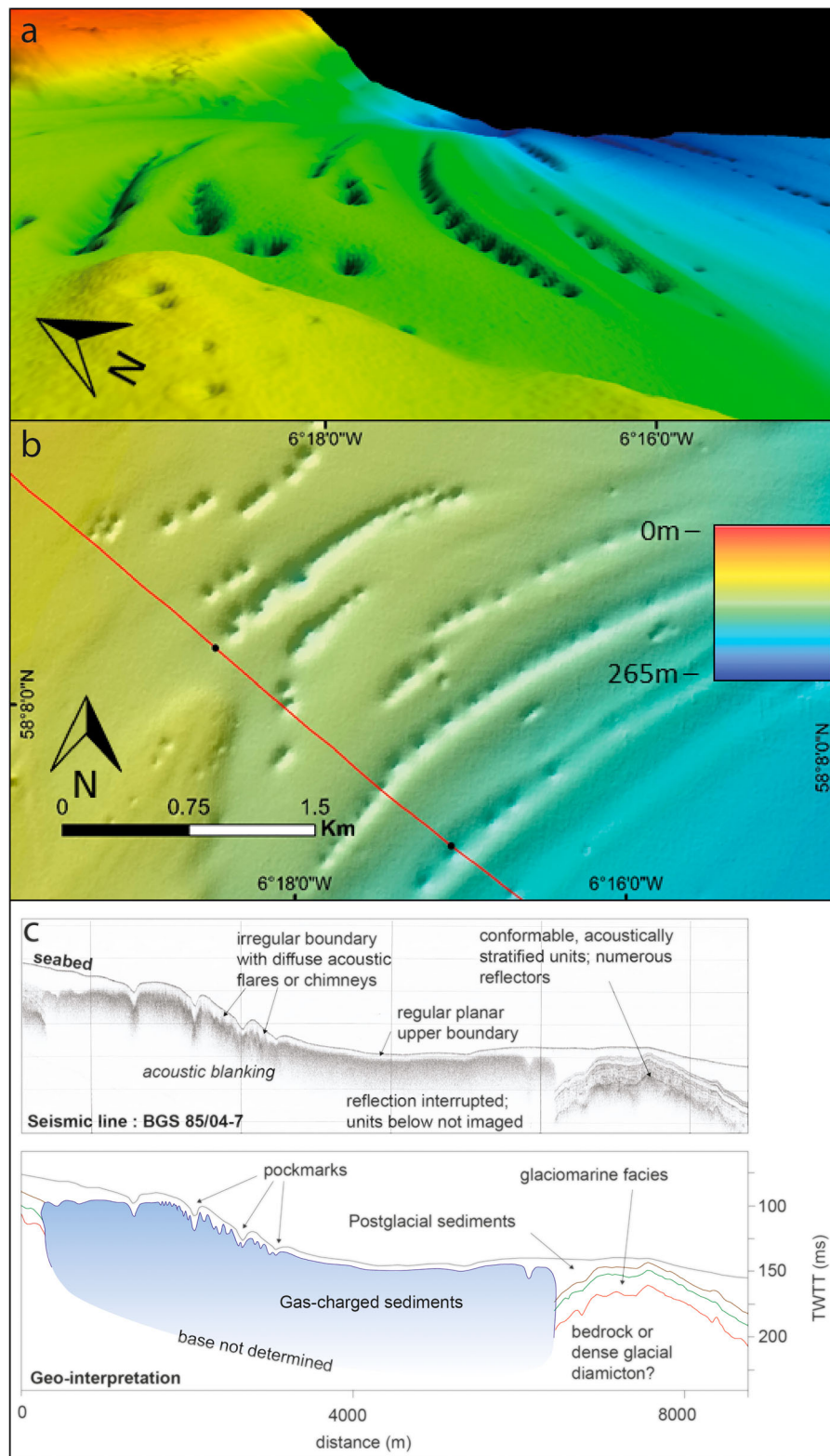


Figure 2. Conical shaped depressions within the Stornoway bay study site. (a) 3D bathymetric image showing the conical shaped depressions. (b) Bathymetric raster within ArcGIS showing the distribution of pockmarks, alongside the position of a 1978 pinger seismic line. (c) 1978 pinger seismic line showing the pockmarks on the seabed (P) and the irregular horizon shown by the yellow line that indicates the occurrence of acoustic turbidity.

use the 'Filter-based Clip' within the BGS toolbox to isolate the main regions of interest. By clipping the raster surface to the regions that contained the features of interest, we reduced the mapping time and removed the effect large basins have on the mapping

process. From this point it is possible to select several methods that can transform the raster into a derived terrain that can highlight various bathymetric characteristics and aid the feature recognition process. Tools that proved most useful were the

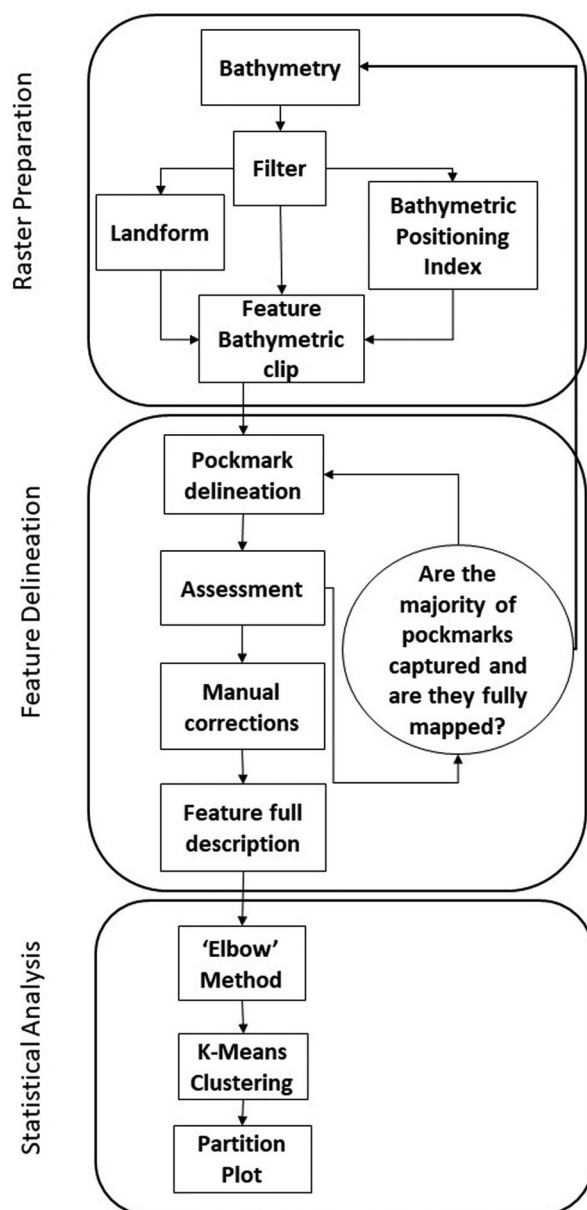


Figure 3. Schematic showing the workflow of pockmark delineation in ArcGIS 10.4 followed by the statistical analysis in R.

‘Landform’ tool available in the ‘Geomorphometry and Gradient Metrics’ toolbox (Evans, Oakleaf, & Cushman, 2014) which highlights regions of concavity/convexity and the fine and broad scale ‘Bathymetric Positioning Index’ (BPI) tools available in the ‘Benthic Terrain Modeler’ toolbox (Walbridge, Slocum, Pobuda, & Wright, 2018). Any number of methods can be used at this point and it was found that several are required to be tested in order to achieve the best result from the mapping toolbox. In order to achieve the results presented here it was found that a landform-derived surface and a fine/broad scale BPI surface provided a suitable raster that highlighted the pockmarks and allowed for the most accurate delineation. Therefore a BPI surface was used for most of the regions to delineate the pockmarks. For the region of the North Minch due to the overall featureless bathymetry in regions

where pockmarks have formed the multibeam bathymetry itself was used to identify and delineate the pockmarks.

The second stage involved using the ‘Feature Delineation Bathy’ or the ‘Feature Delineation BPI’ tool within the seabed mapping toolbox. This tool allows for several limits to be set in order to target a specific feature. These limits include: cut-off vertical relief, minimum vertical relief, minimum width, minimum width/length ratio, buffer distance. For a more detailed account of the BGS seabed mapping toolbox see Gafeira et al. (2012, 2018). Just as with the previous step, several passes were required in order to assess the correct thresholds that capture the majority of the pockmarks and delineate them most accurately. This phase of ‘assessment’ is critical for determining the accuracy and efficiency of the mapping. Should the mapping be sub-standard then it is likely that a change in the thresholds of the feature delineation is needed or using a derived terrain from the previous stage may, in fact, be the best input. It is common for the tool to not delineate all features of interest or to incorrectly delineate a selection. In this case, since there are only a few hundred delineated features within each study site and the overall accuracy of the mapping was acceptable, it is possible to assess visually and perform manual corrections to the errors. The toolbox can then be used to calculate a range of morphological characteristics and record them within the attribute table for each delineated feature. Three characteristics of note include: the depth of the pockmark into the seabed, also known as its vertical relief; elongation, calculated as width/length ratio; minimum water depth, which is the depth of the water column to the pockmark ‘fill’ level. We use the key attributes to describe the morphology of the features.

The morphological classification of the pockmarks was conducted using a statistical k-means clustering algorithm (MacQueen, 1967; Wagstaff, Cardie, Rogers, & Schroedl, 2001) within the software R. This approach assigns a set number of clusters to the dataset. A randomly placed centroid for each cluster is inserted into the dataset and as more observations are added to each cluster the centroid position is recalculated as the mean value of the observations within that cluster. Each cluster therefore contains all the observations that are more similar to each other than to members of another cluster. To determine the number of clusters, we used the elbow method (Bholowalia, 2014; Xue, Lee, Wakeham, & Armstrong, 2011). This method examines the ratio of the between sum of squares and total sum of squares for the dataset when we introduce 1–10 clusters. The point at which the gradient of the line changes indicates the desired number of clusters to be set, as each additional cluster added after this point explains less of the variation within the dataset. When we assign each delineated feature a designated

cluster, from the k-mean clustering algorithm, we can assess the amount of error using a partition plot that fits a quadratic function to the separate clusters. The ability for this function to explain the clusters is assessed and a low application error rate value is desired. This process used the ‘partimat’ function within the ‘klaR’ package in R. This method was conducted with several variable combinations, however, the vertical relief: elongation ratio gave the lowest error values. This set of variables also give a good representation of the 3D morphology of the pockmarks. We then integrated these results back into the GIS to spatially visualize the different pockmark classes based on their morphology and distribution across the study sites.

4. Results

4.1. Pockmark classification

From the feature delineation process using the methodology described above (Figure 3) we have identified 1019 conical shaped depressions. These have been interpreted as pockmarks – the main lines of evidence for this are discussed further (see Discussion).

The elongation values for each of the delineated pockmarks (Figure 4(a)) show that most of the elongated forms are present within the extra-fjordic settings. The majority of the circular forms are to be found within the fjord approach/glaciated bays, which then skews gradually as a result of a few elongated forms also present within this setting. The fjordic setting also appears to be mostly circular forms but with more elongated pockmarks than within the fjord approach/ glaciated bay setting.

The vertical relief values for each pockmark have also been recorded in each setting (Figure 4(b)). We can see that the deepest pockmarks are recorded within the Fjord approaches/ glaciated bays and the fjordic

settings. The majority of the shallowest pockmarks are within the extra fjordic settings.

The elbow plot results (Figure 5) show the variance within the pockmark dataset, as a function of the number of clusters chosen. We can see the greatest change in the gradient of the line at 3 clusters ($n = 3$). This shows that if we introduce additional clusters ($n > 3$) the amount of variance explaining each cluster decreases. Therefore 3 clusters provide the most *meaningful* explanation for the variance within the dataset based on the elongation and vertical relief values of the pockmarks. This value is then used to separate the dataset into clusters using the k-means clustering method. From this we recognise three clusters that are reasonably well described using a quadratic function within the partition plot, giving a low application error rate value of 0.026 (Figure 6). On the basis of this statistical morphometric analysis, we define these three classes of pockmarks as: class 1 = ‘deep’ forms, class 2 = ‘regular’ and class 3 = ‘elongate’.

4.2. Pockmark class distribution

Table 1 briefly outlines the type and relative frequency of pockmarks in each bathymetric study area, from north to south.

5. Discussion and conclusions

The conical depressions we have mapped in coastal (territorial) waters around Western Scotland are interpreted as pockmarks based on: (i) their exclusive occurrence in seabed sediment; (ii) their morphological similarity to other pockmarks mapped elsewhere in European shelf seas; (iii) their association with regions of acoustic (gas) blanking in seismic records (Figure 2).

We have mapped 1019 pockmark forms between 56.1°N and 58°N within different bathymetric settings all within west coast Scottish inshore (territorial)

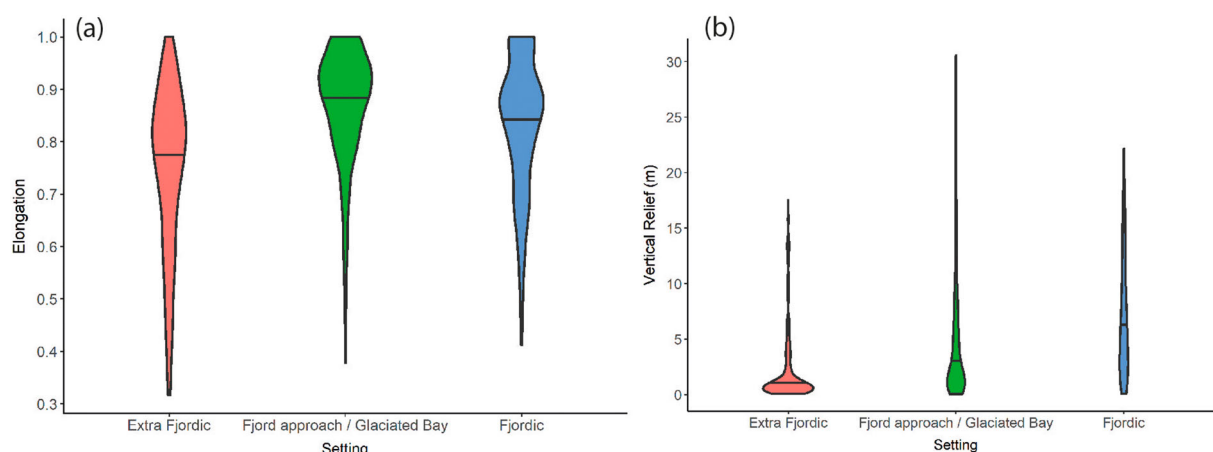


Figure 4. Morphological characteristics of pockmarks within each environmental setting. (a) Pockmark elongation values. (b) Pockmark vertical relief (Depth).

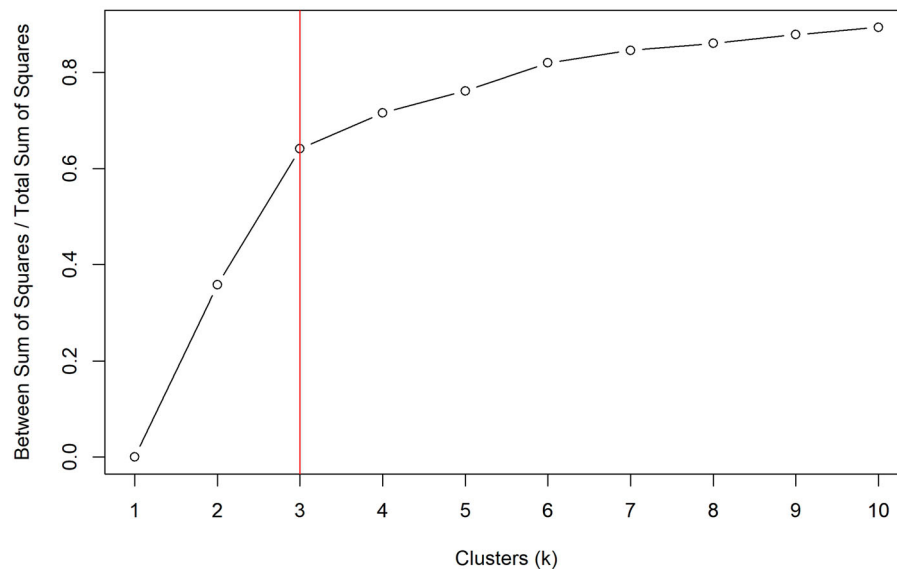


Figure 5. 'Elbow plot' showing the variance of the dataset as a function of the number of clusters we chose to set. Here we can see a change in the angle of the line at three clusters.

waters (<12 nm offshore). This work represents the first widespread and detailed mapping of pockmarks around western Scotland. The map, figures and accompanying morphological data show the pockmark distributions in six typical fjords (Loch Broom, Little Loch Broom, Loch Slapin, Loch Linnhe, Loch Spelve and Loch Melfort); the approaches to those fjords (i.e. Stornoway Bay, the Summer Isles, Firth of Lorn, Arisaig Bay and Inner Sea of Hebrides regions) and more-distal 'extra-fjordic' waters (i.e. the North Minch) – covering a total area of 2019 km². However, our dataset only covers these discrete regions, hence the map

does not represent a complete record of all pockmarks around western Scotland. Many more are likely to exist in other fjordic and further-offshore sedimentary environments. At the moment these areas lie outside our geographical region of interest or have not yet been surveyed with MBES.

The elongation and vertical relief (Figure 4) of the pockmarks were chosen as key morphological metrics to explore possible feature classes. Pockmark elongation most likely represents the effects of local hydrographic conditions (Gafeira et al., 2012; Hovland, 1983; Picard et al., 2018), whereas the depth or vertical relief of the

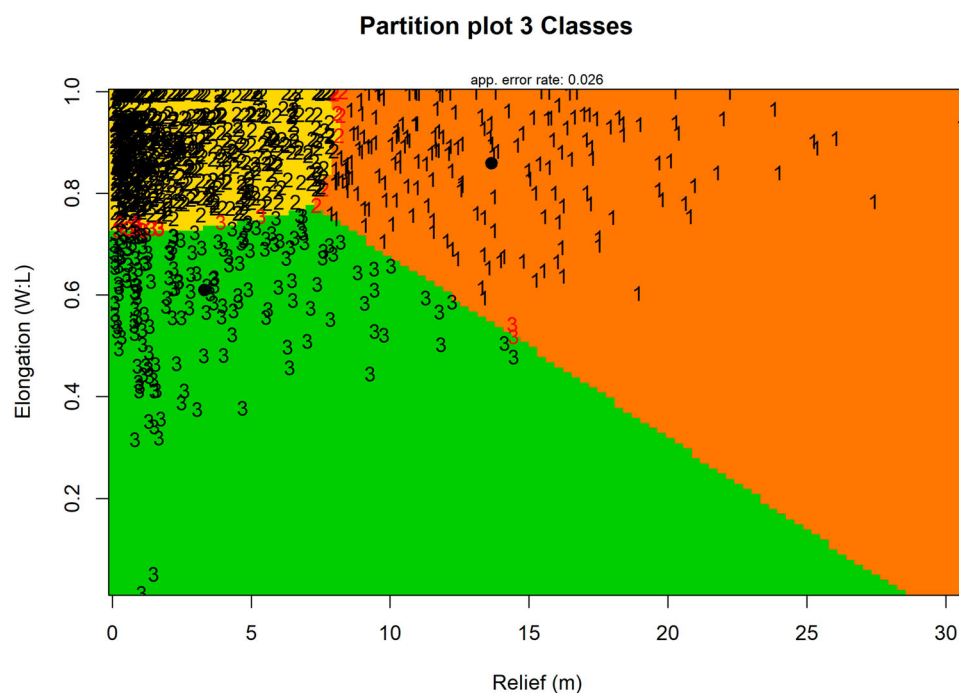


Figure 6. Partition plot showing the results of Elongation as a function of the vertical relief of pockmarks when separated into three clusters. This gives an error value of features that do not separate into the clusters that they have been designated.

Table 1. Percentage of pockmark types within each study site.

Region	Area Description	Area (Km ²)	No. of Pockmarks	Regular (%)	Elongate (%)	Deep (%)
Stornoway Bay	Fjord Approach/ Glaciated Bay	86.4	191	91	4	5
North Minch	Extra-Fjordic	876.8	178	73	27	0
Summer Isles	Fjord Approach/ Glaciated Bay	232.1	70	79	17	4
Loch Broom	Fjord	18.1	23	35	61	4
Little Loch Broom	Fjord	24.1	18	72	28	0
Loch Slapin Approach	Fjord Approach/ Glaciated Bay	82.1	42	45	55	0
Inner Sea of Hebrides	Extra Fjordic	205.1	66	38	39	23
Arisaig Bay	Fjord Approach/ Glaciated Bay	125.8	69	16	16	15
Loch Linnhe	Fjord	168.3	169	51	17	32
Firth of Lorn	Fjord Approach/ Glaciated Bay	161.2	123	54	2	44
Loch Spelve	Fjord	9.8	13	92	8	0
Loch Melfort	Fjord	29.3	38	26	3	71

pockmark more closely relates to activity status of pockmarks; with deeper pockmarks likely to have been active for longer periods of time or to have experienced a more intense venting of gas (forcing more sediment into suspension), alternatively the sediment characteristics of the area might allow deeper and steep pockmark walls to form without collapsing. In either case it is likely that the different hydrographic conditions and history of gas venting have formed pockmarks with different morphologies. Therefore we have defined three morphological classes based on a statistical analysis of pockmark shape and depth; these three classes best represent the different forms of pockmark found western Scotland (with a small application error) (Figure 7). **Deep** pockmarks (class 1) are relatively rare but could be unusually

deep for two main reasons: they have been active for longer periods of time, or they were the site of higher-magnitude gas venting. **Regular** pockmarks (class 2) are the most common and conform with relatively shallow width:depth shape profile. The majority of mapped features fall within this category. **Elongate** pockmarks (class 3), have shallow depth profiles with the deepest point located towards one end. The pockmark becoming elongated over time owing to the dominant prevailing hydrographic conditions.

Regional trends in pockmark morphology exist across the dataset; these are discussed very briefly here as this forms the basis of more detailed work (in preparation). Elongate forms are seen to be proportionately more common within Loch Broom, Little

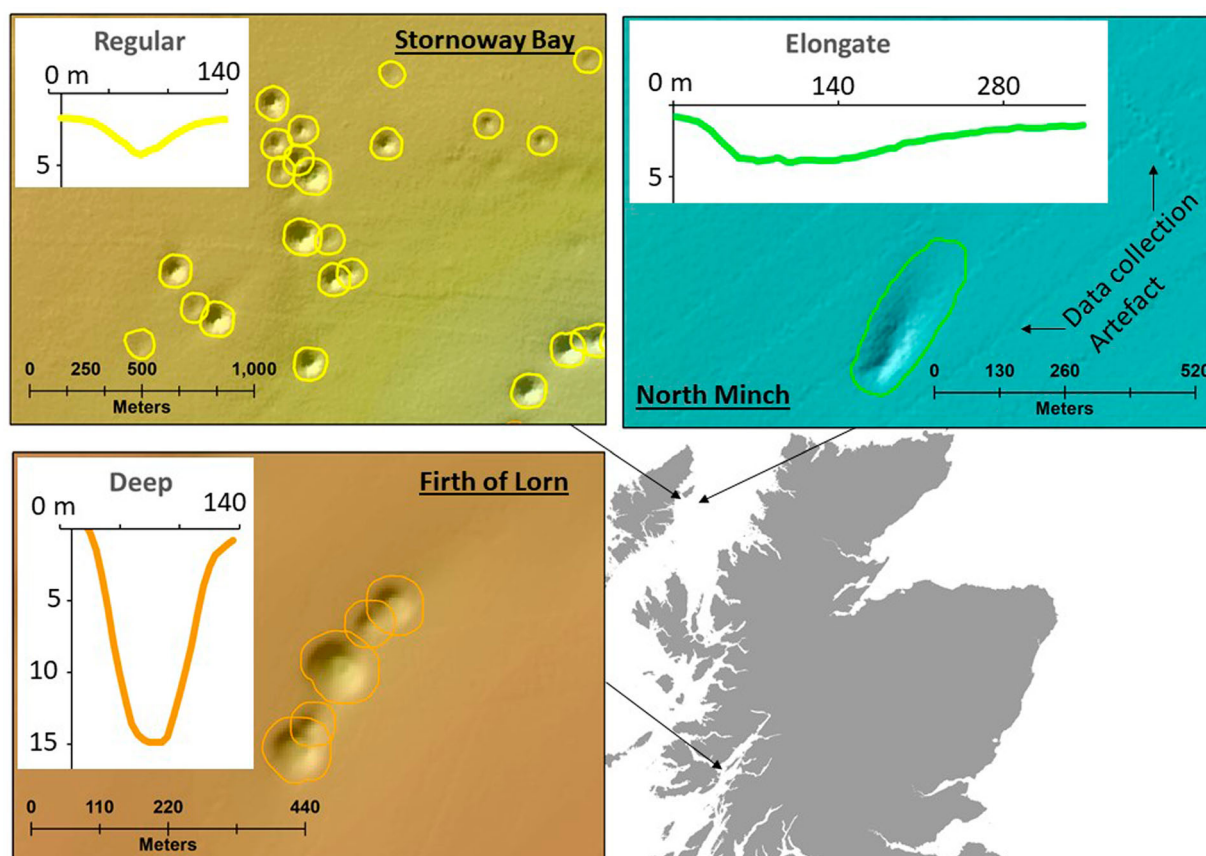


Figure 7. Identified pockmark classes alongside their generic profiles. (Yellow) Common pockmarks, (orange) Deep pockmarks, (green) Elongate pockmarks.

Loch Broom, North Minch, Loch Slapin and Inner Sea of Hebrides. In all these localities it is likely that higher-than-average or sustained bottom currents have acted to scour and sculpt features in the direction of prevailing currents (Hovland, 1983; Picard et al., 2018). Interestingly, deep pockmarks are rare or absent in those settings where elongated forms are relatively common, possibly related to several variables such as a reduced activity status; where pockmarks do not have the same capacity to have a single large venting episode. Equally the sediment characteristics of the region might be unable to facilitate deep, steep walls and therefore infill. In either of the above cases the active venting of the pockmark would form with low slope angles and the local hydrographic conditions would remove material from the region and form the tail of the pockmark. Deep pockmarks are proportionately more common in the southern study sites around the Firth of Lorn as well as in Arisaig Bay and Inner Sea of Hebrides. This may indicate that gas venting was more intense within these regions than in other settings, as such they may represent a more pristine form of pockmark that has been unaffected by sedimentation or local currents. Alternatively, the sediment physical properties of the region may be more conducive to forming steep sided pockmarks. Elongate forms are generally rare in the southern sites suggesting a lack of strong bottom currents in these more protected inshore settings.

The recognition of three classes of pockmarks present within the inshore waters of western Scotland has highlighted the variability in morphology and the spatial distribution patterns of these gas-release features. These morphological differences indicate different styles of formation as a result of their activity history and the sedimentary/ hydrographic characteristics of the regions they form in. The size and number of pockmarks around western Scotland indicate the range of carbon-rich environments present, that extend the main carbon reservoirs previously discovered within the fjordic settings alone (Smeaton et al., 2016, 2017). From the findings of this research it is believed that pockmarks are a useful indicator of past and still present carbon stores. The relationship between pockmark morphology/spatial distribution and the potential volume of gas released remains to be investigated.

Software

The maps were produced in ArcGIS 10.4 using the British National Grid co-ordinate reference system. Mapping of features was achieved using several Add-ins to the ArcGIS toolbox including the BGS Seabed Mapping Toolbox, the Benthic Terrain Modeler and the Geomorphometry and Gradient Metrics toolbox. Pie charts showing the percentages of pockmarks of

that class within each study site were produced in Microsoft Excel. The statistical software programme R was used for the statistical analysis, where the *KlaR* package was used to produce the partition plots.

Data

Datasets used within this study are made available through the ADMIRALTY Marine Data Portal (<https://data.admiralty.co.uk/portal/apps/sites/#/marine-data-portal>).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

- Arosio, R., & Howe, J. (2018). Lateglacial to Holocene palaeoenvironmental change in the Muck Deep, offshore western Scotland. *Scottish Journal of Geology*, 54, 99–114.
- Best, A. I., Richardson, M. D., Boudreau, B. P., Judd, A. G., Leifer, I., Lyons, A. P., ... Wheeler, S. J. (2006). Shallow seabed methane Gas could pose coastal hazard. *EOS, Transactions, American Geophysical Union*, 87, 216–217. doi:10.1130/G21259.1.Fleischer
- Bholowalia, P. (2014). EBK-Means: A clustering Technique based on elbow method and K-means in WSN. *International Journal of Computer Applications*, 105, 17–24.
- Bradwell, T., Stoker, M., & Larter, R. (2007). Geomorphological signature and flow dynamics of The Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science*, 22, 609–617. doi:10.1002/jqs
- Bradwell, T., & Stoker, M. S. (2015). Submarine sediment and landform record of a palaeo-ice stream within the British-Irish ice sheet. *Boreas*, 44, 255–276. doi:10.1111/bor.12111
- Burrows, M. T., Kamenos, N. A., Hughes, D. J., Stahl, H., Howe, J. A., & Tett, P. (2014). Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal

- and marine environment. *Scottish Natural Heritage Commissioned Report No. 761*.
- Çifi, G., Dondurur, D., & Ergün, M. (2003). Deep and shallow structures of large pockmarks in the Turkish shelf, Eastern Black Sea. *Geo-Marine Letters*, 23, 311–322. doi:10.1007/s00367-003-0138-x
- Dove, D., Arosio, R., Finlayson, A., Bradwell, T., & Howe, J. A. (2015). Submarine glacial landforms record Late Pleistocene ice-sheet dynamics, Inner Hebrides, Scotland. *Quaternary Science Reviews*, 123, 76–90. doi:10.1016/j.quascirev.2015.06.012
- Evans, J., Oakleaf, J., & Cushman, S. (2014). An ArcGIS Toolbox for Surface Gradient and Geomorphometric Modeling.
- Fyfe, J. A., Long, D., & Evans, D. (1993). *The Geology of the Malin–hebrides Sea Area*. London: HMSO for the British Geological Survey. <http://pubs.bgs.ac.uk/publications.html?pubID=B01845>.
- Gafeira, J., Dolan, M., & Monteys, X. (2018). Geomorphometric Characterization of pockmarks by using a GIS-based semi-automated toolbox. *Geosciences*, 8, 154. doi:10.3390/geosciences8050154
- Gafeira, J., & Long, D. (2015a). *Geological investigation of pockmarks in the Braemar Pockmarks and surrounding area* (JNCC Report No 571). JNCC Peter, 1–92.
- Gafeira, J., & Long, D. (2015b). *Geological investigation of pockmarks in the Scanner Pockmark SCI area* (JNCC Report No. 570).
- Gafeira, J., Long, D., & Diaz-Doce, D. (2012). Semi-automated characterisation of seabed pockmarks in the central North Sea. *Near Surface Geophysics*, 10, 303–315. doi:10.3997/1873-0604.2012018
- Hillman, J. I. T., Gorman, A. R., & Pecher, I. A. (2015). Geostatistical analysis of seafloor depressions on the southeast margin of New Zealand's south Island — Investigating the impact of dynamic near seafloor processes on geomorphology. *Marine Geology*, 360, 70–83. doi:10.1016/j.margeo.2014.11.016
- Hovland, M. (1983). Elongated depressions associated with pockmarks in the western slope of the Norwegian Trench. *Marine Geology*, 51, 35–46. doi:10.1016/0025-3227(83)90087-7
- Hovland, M., Heggland, R., De Vries, M. H., & Tjelta, T. I. (2010). Unit-pockmarks and their potential significance for predicting fluid flow. *Marine and Petroleum Geology*, 27, 1190–1199. doi:10.1016/j.marpetgeo.2010.02.005
- Hovland, M., & Judd, A. (1988). *Seabed pockmarks and seepages: Impact on geology, biology and the marine environment*. London: Graham & Trotman.
- Howe, J. A., Austin, W. E. N., Forwick, M., Paetzel, M., Harland, R., & Cage, A. G. (2010). Fjord systems and archives: A review. *Geological Society, London, Special Publications*, 344, 5–15. doi:10.1144/SP344.2
- Howe, J. A., Dove, D., Bradwell, T., & Gafeira, J. (2012). Submarine geomorphology and glacial history of the Sea of the Hebrides, UK. *Marine Geology*, 315–318, 64–76. doi:10.1016/j.margeo.2012.06.005
- IHO Standards for Hydrographic Surveys. (2008). 5th ed. International Hydrographic Bureau, doi:10.1192/bjp.112.483.211-a
- JNCC. (2018). Offshore Special Area of Conservation: Scanner pockmark (SAC). SAC Selection Assessment Document, 32, 1–14.
- Judd, A., & Hovland, M. (2007). *Seabed fluid flow: The impact on geology, biology and the marine environment seabed fluid flow impact of geology, biology and the*. Cambridge: Cambridge University Press.
- King, L. H., & Maclean, B. (1970). Pockmarks on the scotian shelf. *Geological Society of America Bulletin*, 81, 3141–3148.
- Krämer, K., Holler, P., Herbst, G., Bratek, A., Ahmerkamp, S., Neumann, A., ... Winter, C. (2017). Abrupt emergence of a large pockmark field in the German Bight, southeastern North Sea. *Scientific Reports*, 7, 1–8. doi:10.1038/s41598-017-05536-1
- MacQueen, J. (1967). Some methods for classification and analysis of multivariate observations. In: *Proceedings of the Fifth Symposium on Math, Statistics, and Probability*. Berkeley, CA, University of California Press, 281–297. doi:10.1007/s11665-016-2173-6
- Marinaro, G., Etiope, G., Bue, N. L., Favali, P., Papatheodorou, G., Christodoulou, D., ... Rolin, J.-F. (2006). Monitoring of a methane-seeping pockmark by cabled benthic observatory (Patras Gulf, Greece). *Geo-Marine Letters*, 26, 297–302. doi:10.1007/s00367-006-0040-4
- Panieri, G., Büinz, S., Fornari, D. J., Escartin, J., Serov, P., Jansson, P., ... Gracias, N. (2017). An integrated view of the methane system in the pockmarks at Vestnesa Ridge, 79°N. *Marine Geology*, 390, 282–300. doi:10.1016/j.margeo.2017.06.006
- Papatheodorou, G., Hasiotis, T., & Ferentinos, G. (1993). Gas-charged sediments in the Aegean and Ionian seas, Greece. *Marine Geology*, 112, 171–184. doi:10.1016/0025-3227(93)90167-T
- Picard, K., Radke, L., Williams, D., Nicholas, W., Siwabessy, P., Howard, F., ... Nichol, S. (2018). Origin of high density seabed pockmark fields and their Use in Inferring bottom currents. *Geosciences*, 8, 195. doi:10.3390/geosciences8060195
- Pilcher, R., & Argent, J. (2007). Mega-pockmarks and linear pockmark trains on the west African continental margin. *Marine Geology*, 244, 15–32. doi:10.1016/j.margeo.2007.05.002
- Scottish Adjacent Waters Boundaries Order. (1999). <http://www.legislation.gov.uk/ukxi/1999/1126/contents/made>
- Smeaton, C., Austin, W. E. N., Davies, A. L., Baltzer, A., Abell, R. E., & Howe, J. A. (2016). Substantial stores of sedimentary carbon held in mid-latitude fjords. *Biogeosciences (online)*, 13, 5771–5787. doi:10.5194/bg-13-5771-2016
- Smeaton, C., Austin, W. E. N., Davies, A. L., Baltzer, A., Howe, J. A., & Baxter, J. M. (2017). Scotland's forgotten carbon: A national assessment of mid-latitude fjord sedimentary carbon stocks. *Biogeosciences (online)*, 14, 5663–5674. doi:10.5194/bg-14-5663-2017
- Smith, R. W., Bianchi, T. S., Allison, M., Savage, C., & Galy, V. (2015). High rates of organic carbon burial in fjord sediments globally. *Nature Geoscience*, 8, 450–453. doi:10.1038/NGEO2421
- Solheim, A., & Elverhøi, A. (1993). Gas-related sea floor craters in the Barents Sea. *Geo-Marine Letters*, 13, 235–243. doi:10.1007/BF01207753
- Stoker, M., & Bradwell, T. (2009). Neotectonic deformation in a Scottish fjord, Loch Broom, NW Scotland. *Scottish Journal of Geology*, 45, 107–116. doi:10.1144/0036-9276/01-393
- Stoker, M., Bradwell, T., Wilson, C., Harper, C., Smith, D., & Brett, C. (2006). Pristine fjord landsystem revealed on the sea bed in the Summer Isles region, NW Scotland. *Scottish Journal of Geology*, 42, 89–99. doi:10.1144/sjg42020089
- Syvitski, J. P. M., Burrell, D. C., & Skei, J. M. (1987). *Fjords – processes and products*. New York: Springer.
- Wagstaff, K., Cardie, C., Rogers, S., & Schroedl, S. (2001). Constrained K-means clustering with background knowledge. In: *Proceedings of the eighteenth international*

- conference on machine learning*. 577–584. doi:10.1109/TPAMI.2002.1017616
- Walbridge, S., Slocum, N., Pobuda, M., & Wright, D. (2018). Unified geomorphological analysis workflows with Benthic Terrain Modeler. *Geosciences*, 8, doi:10.3390/geosciences8030094
- Whiticar, M. J., & Werner, F. (1981). Pockmarks: Submarine vents of natural gas or freshwater seeps? *Geo-Marine Letters*, 1, 193–199. doi:10.1007/BF02462433
- Xue, J., Lee, C., Wakeham, S. G., & Armstrong, R. A. (2011). Using principal components analysis (PCA) with cluster analysis to study the organic geochemistry of sinking particles in the ocean. *Organic Geochemistry*, 42, 356–367. doi:10.1016/j.orggeochem.2011.01.012